Experimental Behaviour of Reinforced Concrete Beams Strengthened with Prestressed CFRP Shear Straps

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Abstract

One promising means of increasing the capacity of existing shear-deficient beams is to strengthen the structure using external prestressed carbon fibre reinforced polymer (CFRP) straps. In this system, layers of CFRP tape are wrapped around a beam to form a strap which acts like a discrete unbonded vertical prestressing tendon. Experiments were undertaken to investigate the influence of the strap spacing, the strap stiffness, the initial strap prestress level and/or any pre-existing damage on the strengthened behaviour and mode of failure. An unstrengthened control beam was tested and failed in shear. In contrast, all of the strengthened beams showed a significant increase in their ultimate load capacity with several of the strengthened beams failing in flexure. A number of different failure modes were noted and initial guidelines on the design parameters that influence the propensity for a particular failure mode were developed.

KEYWORDS: shear; concrete; prestressed; fiber reinforced polymers; strengthening

Introduction

Much of our existing reinforced concrete infrastructure dates from the 1960's and 1970's. Over the last 30 or 40 years, traffic volumes and loads have increased resulting in a need to enhance the strength capacity of existing infrastructure. In cases where design errors are noted, or deterioration has taken place, then the priority may simply be to upgrade the structure to meet the original specified design capacity.

The use of strong, light-weight and durable fibre reinforced polymers (FRPs) to provide additional external reinforcement for existing structures is an attractive solution. For shear strengthening applications, most of the FRP systems considered to date have been passive bonded systems where FRP sheets or laminates are adhesively bonded to the concrete surface. The current work considers a fundamentally different system based on the use of prestressed carbon FRP (CFRP) straps.

The CFRP reinforcing elements are installed by wrapping thin layers of CFRP tape around a beam to form a closed loop or strap. A strap can be prestressed and acts like a discrete unbonded vertical prestressed tendon. The system is very versatile and the number of tape layers can be varied to meet a particular stiffness or strength requirement e.g. a strap with 10 tape layers has twice the stiffness and strength of a strap with 5 tape layers. The level of initial prestress force can also be chosen to suit design requirements.

A prestressed steel shear strap system was used in 1957 to strengthen reinforced concrete warehouse frames (Elstner, R C & Hognestad, E 1957). However, the susceptibility of steel to corrosion and the relatively high weight of the material are distinct disadvantages. The earliest study on the application of prestressed CFRP straps to strengthen reinforced concrete beams was in 1997 and was carried out at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) (Lees, J M et al. 2002). Whereas an unstrengthened control T-beam failed in shear, an equivalent CFRP-strengthened beam failed in a ductile manner after the longitudinal yielding of the main reinforcement with a capacity increase of 40%. Subsequent experiments (Kesse, G et al. 2001) at the University of Cambridge on reinforced concrete T-beams supported the conclusion that the CFRP straps increased the shear capacity of a beam and could prevent a brittle shear failure. Further experimental and analytical work was also carried out at ETH in Zurich where a series of deep beams (150 mm wide by 1200 mm deep) were successfully strengthened using CFRP straps (Stenger, F 2000). The results of all of these research projects have been most promising and the current work aims to extend our understanding of the system performance by considering in detail the factors that govern the strap behaviour and mode of failure of structures strengthened with CFRP straps. This understanding is of particular importance since the straps are elastic and brittle so a knowledge of the true stress and strain in the strap is essential.

The current investigation considers the influence of; the initial strap prestress level, the strap stiffness e.g. number of tape layers, the strap spacing and any existing damage on the strengthened behaviour. By considering different initial prestress levels, the effects of the prestress force on the crack paths, the modes of failure and the level of shear enhancement can be investigated. The stiffness and the spacing of the CFRP straps are also important and will not only affect the structural performance but also have cost implications. In addition, existing structures might have undergone some damage prior to strengthening and it is necessary to ascertain how the straps will behave and modify the shear capacity when there are existing cracks. By considering these various parameters, insight will also be gained regarding the potential technical trade-offs in light of economic and practical constraints i.e. the relative costs of the material and the installation procedures.

Research Significance

The use of prestressed CFRP straps for the shear strength enhancement of existing reinforced concrete structures is an area with great promise. In particular, beams strengthened with CFRP straps have shown significant increases in strength capacity relative to unstrengthened control beams. However, as with any emerging technology, it is important to understand the key system design parameters and the influence of these parameters on possible failure modes. The current work provides further experimental evidence of the strengthened behaviour and provides initial design guidance for unbonded CFRP prestressed shear systems.

Experimental Programme

The experimental series considered unstrengthened reinforced concrete control beams and beams strengthened with prestressed CFRP straps.

Test set-up and procedure

The beams were loaded using a cantilever arrangement. Although a four point loading system is more common, the four point arrangement has two shear spans of equal importance and results in a substantial volume of data. It was therefore felt that a single shear span would provide less data but would be qualitative enough to study the strap behaviour.

Figure 1 shows the layout of the cantilever beam with an end block support. The beam has an overall span of 1200 mm, width of 105 mm and depth of 280 mm. The beam was typically loaded at a distance of 690 mm ($a/d = 3$) from the support. The longitudinal steel reinforcement consisted of two 16 mm diameter bars and two 12 mm diameter bars. The beam also contained two 12 mm diameter compression reinforcement bars. A nominal level of shear reinforcing consisting of 4 mm diameter stirrups at 200 mm spacings was provided. The end block support had dimensions of 300 mm by 680 mm and a width of 105 mm. It was reinforced with 12 mm and 10 mm diameter bars both spaced at approximately 42 and 55 mm centres respectively forming a rectangular mesh (see fig. 1). A smaller amount of reinforcement was initially used in the end block but was later increased to the levels detailed above when the first two control beams cracked at the support. The 0.2% yield stress of the 4 mm, 6 mm and 10 mm bars was around 400 MPa, that of the 12 mm and 16 mm bars was approximately 440 MPa.

The 12 mm wide by 0.16 mm thick CFRP tape used to form the straps had a Young's modulus of 130000 N/mm^2 and an ultimate strain of 11000 μ strain. The mix proportions of the concrete used in all the experiments were $1 : 2.2 : 2.64$ (cement:sand:aggregate) with a maximum aggregate size of 10 mm. The rapid hardening cement mix gave a compressive cube (100 mm) strength f_{cu} of about 40 N/mm^2 after 7 days. If it assumed that the an equivalent cylinder strength f'_c is $\approx 0.8\ f_{cu}$ then this strength would be analogous to $f'_c =$ 32 N/mm^2.

The beams were designed to have a large difference between their unstrengthened shear capacity and their flexural capacity so that, when the straps were incorporated there was a sufficient range over which the capacity enhancement could be measured. For a shear span of 690 mm, BS8110 (British Standards Institution 1985) calculations would suggest that the moment capacity corresponding to a shear failure of the chosen section was about 34.5 kNm (a shear force of 50kN) while the full flexural capacity for the under-reinforced section was 66.2 kNm (a shear force of around 95.9 kN).

The beams were cast on their sides in wooden formwork and vibrated intermittently during placing. Two batches of concrete were required for casting two beams as well as six cubes, six cylinders and two modulus of rupture specimens. The beams and concrete control specimens were covered with a plastic sheet for curing and were removed from the formwork two or three days after casting. Figure 2 shows the rig built to test the beams. The rig consists of 2 braced steel channels (305 mm $\times$ 89 mm $\times$ 8 mm) bolted to the ground.

For the strengthened beams, layers of the unidirectional CFRP thermoplastic tape are wound around the beam web until the desired number of layers is reached. The two outermost layers of the strap are welded together by inserting a thermoplastic material between the two outer layers and heating these to $200°C$. In this way an outer closed loop is formed while the inner tape layers remain unlaminated thereby reducing through-thickness stress concentrations. Strain gauges are attached to the outer and inner strap layers. The straps are not bonded to the concrete.

The prestressing procedure involved the set-up shown in fig. 3. The strap is supported on two semi-elliptical steel pads with a minimum support radius of 20 mm. This radius was selected on the basis of pin-loaded strap results from Winistoerfer (Winistoerfer, A U 1999) who found that, provided the pin diameter was greater than 30 mm, the size of the pin did not significantly influence the load-carrying capacity of the straps. The bottom support pad is fixed to underside of the web of the beam and the top support pad sits in a groove in a rectangular steel plate. This grooved plate is attached to a jack using a threaded rod and plate system. When the jack is loaded it lifts the grooved plate supporting the pad thereby tensioning the strap. A gap is then created underneath the plate and filled with metal shims. When the desired strain is reached, the jack is unloaded and the plate then sits on the shims. Normally the strap is prestressed to a level 20% greater than the required value so that once the jack is released the desired prestress level will remain. The loading apparatus is then dismantled.

Experimental beams

In total, twelve cantilever beams were tested (Table 1 summarises the experimental results). The first four beams were unstrengthened control beams whilst the latter eight beams were strengthened with prestressed CFRP straps. The main differences between the strengthened beams were the strap spacing, the strap stiffness, the initial strap prestressing force and the presence of precracks. To simplify the identification of the different parameters associated with the beams, the following notation was used : **beam number - number of straps - number of layers - level of prestress**. For example, B5-2s-10l-50p refers to beam 5 with 2 straps made of 10 layers of tape each, prestressed to 50 % of the strap ultimate capacity. A beam with two straps will have a clear spacing of 230 mm between the first strap and the support whereas a beam with one strap will have a spacing of 345 mm.

In the unstrengthened beam series, beam 1 was used to test the steel support frame and the experimental setup. There were initially problems with the test set-up both due to cracking in the beam end block support and also excessive steel testing frame deflections. However, these problems were mitigated by increasing the amount of reinforcement in the end block and increasing the stiffness of the steel testing frame. Beams 2 and 4 were then tested to establish the unretrofitted shear capacity. To determine the maximum cross-sectional flexural capacity, beam 3 was designed with larger diameter shear stirrups at 75 mm spacings and was tested with an a/d ratio of 4.5.

For strengthened beams 5 to 10, the initial prestress level in the straps was approximately 50 % of the ultimate strap capacity. For a 10 layer strap this would imply a prestressing force of around 25 kN (the strap capacity is 50 kN) whereas for a 5 layer strap (with a capacity of 25 kN), the corresponding initial prestress force is approximately 12.5 kN. Beams 5 and 10 each had two straps but the strap stiffnesses of the two beams were different (10 layers vs 5 layers). Beams 6 and 9 were strengthened with one strap but again had different strap stiffnesses (5 layers vs 10 layers). Beams 7 and 8 were precracked to a load level of 70% of the unretrofitted ultimate load capacity before being unloaded and strengthened with one 5 layer or two 10 layer straps respectively. Beams 11 and 12 both had two 10 layer straps but different prestress levels (25% (12.5kN) and 5% (2.5 kN)).

Experimental results

The experimental load-displacement curves are shown in fig. 4 where the displacement was measured at the load point. The failure modes and ultimate capacities are summarised in Table 1. All the strengthened beams had a shear capacity at least 50 % higher than that of an equivalent unstrengthened beam. Whereas the unstrengthened beam failed in shear, several of the strengthened beams failed in flexure.

All the beams with a single strap failed in shear; either a dominant crack crossed the strap leading to the rupturing of the strap and subsequent shear failure, or the strap restrained the crack but a weak unstrengthened region adjacent to the strap was created leading to a shear failure. In the case of the beams with two straps; some failed in shear whilst others attained their full flexural capacity.

It was clear from the experimental results that the observed shear failures were not all the same and hence a further classification is required. The observed modes of failure were:

Shear mode 1 (S1) This occurs as a result of a strap failure leading to an overall beam failure in shear e.g. B6 (see fig. 5).

Shear mode 2 (S2) This occurs when a beam fails in shear in an unstrengthened region and the strap does not fail e.g. B9 (see fig. 6).

Shear mode 3 (S3) This occurs when there is extensive crack opening and damage, followed by a strap failure e.g. B12 (see fig. 7).

Flexural mode 1 (F1) Failure of a beam in flexure followed by a strap failure. Very little ductility is observed e.g. B5 (see fig. 8).

Flexural mode 2 (F2) Failure of a beam in flexure with adequate ductility characterised by the yielding of the longitudinal steel eventually followed by concrete crushing e.g. B11 (see fig. 9).

The occurrence of shear mode 2 was primarily dictated by the strap spacing whilst shear modes 1 and 3 depended mainly on the initial strap prestress level and the strap stiffness. The distinction between flexural modes 1 and 2 also depended on both the level of prestress and the strap stiffness. These interactions will be described in more detail in the following sections. It is of note that a finite element (FE) analysis of the experimental beams identified only two of the basic modes of failure, shear mode 2 and flexural mode 2, and did not pick up any of the other failure modes (Kesse, G 2003). This limitation was attributed to the model for the cracked concrete. Further details can be found elsewhere (Kesse, G 2003).

Beam comparison

The experimental results provide an opportunity to compare the behaviour of the beams and identify common and contrasting features. The strap spacing, stiffness and prestress and, to a lesser extent, the initial damage, were all found to have an influence on the strengthened behaviour. In the first instance, each factor will be discussed in isolation. Interactions between the various parameters will then be highlighted.

Strap spacing

To investigate the influence of the strap spacing, beams with the same strap stiffness and the level of prestress but with a different number of straps within the shear span need to be considered. Beams 5 and 9 or beams 6 and 10 can be used since they satisfy this criteria. Beams 5 (2 straps) and 9 (1 strap) had straps with 10 layers of tape whilst the straps in beams 6 (1 strap) and 10 (2 straps) had 5 layers.

Beams 6 and 10 both failed in shear mode 1 although the strap spacing was different. In both beams, the outermost shear crack formed and crossed the straps leading to failure. In effect, the strap was not able to adequately constrain this shear crack and the beam failed in shear.

In contrast, beam 9 failed in shear mode 2 whilst beam 5 failed in flexure mode 1 (limited ductility). Beams 5 and 9 had a higher prestressing force and strap stiffness than beams 6 and 10 and thus the outermost shear crack did not propagate and lead to failure (see fig. 10). Instead beam 9 failed in the unstrengthened region between the strap and the support with a crack angle of around 39°. A similar crack formed in beam 6 but opened concurrently with an outer crack inclined at an angle of 32° reducing to 10° as it passed the strap leading to failure of the strap. These results suggest that the spacing of the straps does not solely influence the capacity and mode of failure but that the interaction of the spacing with the stiffness and initial prestress force in the strap is important.

Codes of practice typically stipulate that the stirrup spacing should not exceed the effective depth of the beam. The CFRP strap spacing in beams 6 and 9 violated this rule whilst that in beams 5 and 10 satisfied this criteria. Since beams 6 and 9 failed in shear it can be concluded that the straps should be spaced at a distance not more than the effective depth of the beam. However, this stipulation in isolation is not sufficient to ensure a flexural failure.

Initial prestress level

Beams 5, 11 and 12 all had two 10 layer straps but the level of prestress differed. The straps in beam 5 were stressed to a level of 50% (25 kN) while those in beam 11 and 12 were stressed to a level of 25% (12.5 kN) and 5% (2.5 kN) respectively.

The crack pattern comparison at 65 kN (see fig. 11) indicates that the prestress force in a strap will first and foremost dictate the load at which the crack will cross the strap in the shear span. Cracks will normally form in a region not subjected to a transverse compressive prestress and then propagate until a region influenced by the strap prestress is encountered. The progress of the crack will then be dictated by the level of prestress.

As the strap prestress increases, the crack angle may also become steeper. This was observed to some extent in the experiments. With a very high level of prestress, it would be possible for the crack to become so steep that it will lead to failure in a region between two straps, but this would also depend on the strap spacing. This will be a subject of further work.

After the crack crosses a strap, the crack behaviour and progress depends on factors such as the interaction between the prestressed strap and aggregate interlock (Kesse, G 2003). Although the compressive prestress force is perceived to be an advantage it should be noted that for a strap with a defined number of layers, a higher initial prestress will lead to a decrease in the available strain capacity for deformation and thus strap failure becomes more likely. However, in beam 5, this was only observed to occur after the beam had attained its full flexural capacity (flexural mode 1).

A very low initial prestress is also undesirable as the crack will easily propagate and lead to a shear failure. Under such circumstances the role of the strap might primarily be to hold together two cracked concrete blocks separated by a shear crack (as observed in beam 12). It is thus analogous to a rigid block arrangement. Shear mode 3 is more likely to occur when the strap prestress is too low. With a low initial prestress, there is a large reserve strain capacity in the straps and hence the yielding and fracturing of the internal steel stirrups is more likely. This was observed in beam 12 before a strap failed.

In summary, a minimum prestress is required for the effective and efficient use of the CFRP straps but there is also a maximum prestress limit required to avoid premature rupturing of straps. For reasons described later, these prescribed limits will depend on factors such as the depth of the beam, long-term effects and the requisite safety factors.

Stiffness of straps

Beams 10 and 11 can be used to investigate the influence of the strap stiffness on the beam behaviour. Beam 10 had two five layer straps each prestressed to around 12.5 kN (50% of the strap's capacity) and failed in shear mode 1 whereas beam 11 had two ten layer straps each prestressed to around 12.5 kN (25% of the strap's ultimate capacity) and failed in flexure mode 2 with significant ductility. Therefore the beams had approximately the same initial prestress force but the straps on beam 11 were twice as stiff as those on beam 10.

Figure 12 shows that the shear cracks crossed the straps at almost the same load (which is consistent with the conclusions from the previous section). However, at 65 kN, the cracks in beam 10 had progressed much further than those in beam 11. A plot of the strap forces for both beams is shown in fig. 13 and the plot indicates broadly similar forces in the straps. However, since the straps did not have the same stiffness, the less stiff straps had to strain more to attain the required force. At higher loads, the crack widths will therefore be much greater in beam 10 than in beam 11.

Thus the stiffness of the strap plays a major role once the crack has crossed the strap.

The stiffness governs how much deformation or crack opening will occur for a given load increment in the strap. The deformation of the strap comes from an increase in the crack width which also depends on the overall crack geometry i.e. as the crack width increases, the crack will also propagate. If the stiffness of the straps is not adequate, crack growth occurs rapidly leading to shear failure.

Effect of pre-cracking

Comparing beams 8 and 5 and also beams 6 and 7, it can be seen from fig. 4 that the existing cracks seemed to influence the stiffness of the beam but did not have a significant influence on the ultimate shear capacity. Although these pre-cracked beams were loaded to 70% of their unstrengthened shear capacity, visual inspection and the readings from the strain gauges tended to indicate that the shear damage at this load was still fairly minimal. It is perceived that if a higher load and/or a different loading arrangement had been applied the results might have been different. In addition, the prestressing force would help to close any existing cracks and thus may be an advantage over a passive strengthening system. Further work is required in this area.

Strengthened behaviour

The main shear resisting mechanisms for a reinforced concrete beam strengthened with CFRP straps are dowel action, aggregate interlock, the concrete compression zone, any internal steel stirrups and the external CFRP strap(s).

In contrast to the internal steel stirrups which are ductile, the CFRP straps are elastic and brittle. It is therefore essential to consider both equilibrium *and* compatibility as it is not possible to rely on the ductile redistribution of stress. For a given applied load and strap stiffness, the overall equilibrium and compatibility of the system will dictate the force in the strap. This force will have a component due to the initial prestress force (P_o) and an additional force component due to the crack opening ($P_A = \Delta\epsilon_{st} A_{st} E_{st}$ where $\Delta\epsilon_{st}$ is the additional strap strain, A_{st} is the strap area and E_{st} is the Young's modulus of elasticity of the strap). As the vertical leg of the strap is not bonded to the concrete and is effectively anchored at points on the top and bottom steel support pads, the additional strap strain $\Delta\epsilon_{st}$ is approximately equal to the summation of the crack widths at the location of the strap, δ_{ctot}, divided by the beam height, h.

Consider the case where a particular strap force is required for equilibrium. If a high initial prestress force is chosen then the required crack opening and propagation will be small and the overall force in strap will be mostly be due to the initial prestress force. On the other hand if the selected initial prestress force is small then a greater crack opening force component is required to induce the requisite additional strap force so that equilibrium can be attained. This behaviour is highlighted by recapping the following observations.

In B12-2s-10l-5p (with a very low initial prestress force) a greater deformation was required to create the necessary strap force and the crack pattern was much more extensive than in the case of B5-2s-10l-50p where a higher initial prestress force was used (see fig. 11). In beam 12, any increase in strap force was primarily a function of the crack opening component, P_A. As the crack openings increased, the internal steel stirrups yielded and the aggregate interlock resistance along the crack potentially decreased. The straps then carried a greater load, and the strap strain and thus the crack widths, increased. The larger crack widths eventually lead to the internal steel stirrups reaching their fracture strain thereby shedding additional load to the straps. The strap force results for beam 12 plotted in fig. 13 provide insight into this failure sequence (shear mode 3) where there is a dramatic increase in strap strain (and strap force) above a load of around 80 kN.

Consider also B10-2s-5l-50p and B11-2s-10l-25p which had the same initial prestress force (P_o = 12.5kN) but different strap stiffnesses. To provide a given P_A, a strap in beam 11 would have to deform twice as much as a strap in beam 10 which means that the corresponding δ_{ctot} in beam 11 would also have to be twice that of beam 10 resulting in more extensive crack propagation (see fig. 12). Figure 13 confirms a broad similarity in the total forces in the straps in the two beams for a given load up to a load of around 75 kN, at which point it appears that the larger crack widths start to influence the other shear resisting mechanisms since the strap forces in beam 10 increase more rapidly than beam 11. These experimental results support the conclusion that the prestress and stiffness effects interact to provide the strap force required for equilibrium. It is thus the total force across the crack that is important. This interaction suggests that for design purposes the initial prestress and stiffness should be considered together at the ultimate limit state. There is a certain freedom to select either the strap area or the initial prestress and to design the other parameter to ensure flexural failure. The selection may be governed by the cost of material versus the cost of the prestressing operation.

It is expected that the presence of the CFRP straps will also influence the magnitude of the other shear resisting mechanisms. Walraven (Walraven, J C 1981) has shown that the amount of aggregate interlock is a function of the crack width and the force across the crack. So in principle, provided a shear-compression or strap failure did not occur, a stiffer strap with a higher initial prestress force would be preferable as a higher force is induced for a given crack width. The strap will potentially reduce the shear stress in the compression zone at a particular load increment and also confine the concrete compression zone increasing the ability of the concrete compression zone to carry additional shear forces (Kotsovos, M D 1988). Dowel action may be enhanced as the vertical prestress could mitigate longitudinal splitting along the tensile reinforcement. A further consideration is the load sharing between the internal stirrups and the vertical straps.

The results of the experimental series have been summarised in a design flowchart as shown in fig. 14. The design flowchart provides an overview of the key parameters and the limits that must be imposed. If the strap spacing and/or strap stiffness and/or initial prestress level are problematic, the member will fail in one of the three shear modes. Shear mode 2 is likely to occur when the strap stiffness and prestress level are satisfactory but the strap spacing is excessive. In such a case, weak regions will form between straps where shear cracks propagate in an unrestrained fashion (beam 9). The distinction between shear mode 1 or 3 depends on the strap stiffness and prestress which basically influence the crack widths during the later stages of loading. In shear mode 1, the strap stiffness and prestress are sufficiently high to ensure that a strap failure is associated with smaller crack openings. Hence, the internal steel stirrups do not fracture and the concrete load-carrying capacity is not severely compromised (beams 6, 7 and 10). In contrast, shear mode 3 is characterised by a combination of initial prestress and stiffness levels that result in large crack openings being required to induce the necessary strap forces required for equilibrium (beam 12).

There is an important caveat in the results presented here in that the beam height in the current work was relatively shallow. The straps are unbonded and as the height of the beam increases, for a given crack opening δ_{ctot}, the additional force due to crack opening P_A will be lower since if the height h increases, $\Delta\epsilon_{st}$ will reduce for a given δ_{ctot}. This would necessitate relatively large crack openings in order to significantly increase P_A. Hence, a higher initial prestress force would be advantageous and indeed this was found in the work of Stenger (Stenger, F 2000) on deep beams where the initial prestress force made a significant difference to the strengthened capacity. This implies that size effects must be considered when selecting initial prestress and stiffness of straps and additional studies are required to quantify these effects. In addition, the upper prestress limit will also depend on the desired level of reserve strap strain capacity.

Additional areas for further research include the influence of the span to depth ratios on the strengthened behaviour and further investigations on the practical installation of the strap system.

Conclusions

The prestressed CFRP strap strengthening system shows great promise and is an effective means of significantly increasing the shear capacity of existing concrete structures. The results of an experimental series where unstrengthened and strengthened beams were tested demonstrate that the interaction between the strap spacing, the initial prestress force and the strap stiffness has an important influence on the strengthened behaviour. A limited amount of pre-existing damage seemed to affect the overall beam stiffness but not the ultimate load capacity. A total of five failure modes were identified and initial guidance on the factors that influence the likelihood of a particular failure mode were presented. As the CFRP straps are elastic and brittle, any analysis of their behaviour must take into account the compatibility of the system. If the proper strap spacing, initial prestress and stiffness are chosen it was possible for the failure mode of the beams tested in the current study to change from a brittle shear failure to a ductile failure in flexure at a load that was 90% higher than the ultimate load capacity of an equivalent unstrengthened beam. It is noted that size effects and the interaction of the prestressed strap with other shear resistance mechanisms such as aggregate interlock and the concrete compressive zone should be the subject of further work.

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Tables

Table 1: Summary of experimental results

Beam number	a/d **ratio**	**No. of straps**	**No. of tape layers**	**Level of prestress** (%)	f_{cu}/f'_c (N/mm^2)	f_t (N/mm^2)	**Mode of failure**	**Strap failure**	**Peak shear load (kN)**	**Associated moment capacity (kNm)**
B1-ns-nl	3	-	-	-	62.3/49.8	3.84	S	-	25.0	17.3
B2-ns-nl	3	-	-	-	62.3/49.8	3.84	S	-	52.0	35.9
B3-ns-nl	4.5	-	-	-	48.7/39.0	3.60	F	-	65.5	67.8
B4-ns-nl	3	-	-	-	48.7/39.0	3.60	S	-	48.0*	33.1
B5-2s-10l-50p	3	2	10	50	49.7/39.8	2.87	F1	yes (strap 1)	97.7	67.4
B6-1s-5l-50p	3	1	5	50	47.9/38.3	2.87	S1	yes	81.2	56.0
B7-1s-5l-50p-34d	3	1	5	50	43.5/34.7	3.13	S1	yes	75.5	52.0
B8-2s-10l-50p-34d	3	2	10	50	44.0/35.2	3.80	F1	no	96.1	66.3
B9-1s-10l-50p	3	1	10	50	41.0/32.8	3.24	S2	no	87.6	60.4
B10-2s-5l-50p	3	2	5	50	43.5/34.8	3.43	S1	yes (straps 1&2)	79.8	55.0
B11-2s-10l-25p	3	2	10	25	45.9/36.7	3.23	F2	no	97.0	66.3
B12-2s-10l-5p	3	2	10	5	45.9/36.7	3.23	S3	yes (straps 1&2)	89.0	61.4

* -	test stopped	F1 -	mode 1 flexural failure	S -	diagonal tension failure	S2 -	mode 2 shear failure
F -	flexural failure	F2 -	mode 2 flexural failure	S1-	mode 1 shear failure	S3 -	mode 3 shear failure

Figures

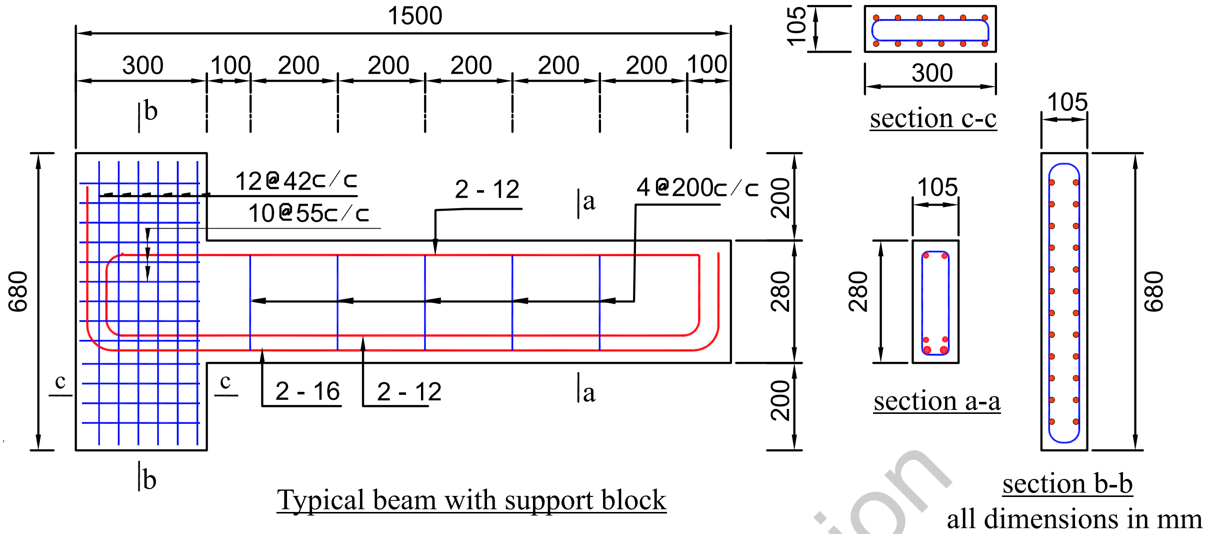


Figure 1: Unstrengthened beam layout

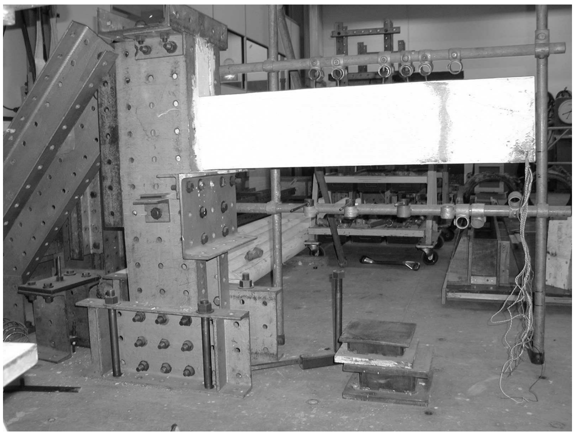


Figure 2: Testing frame

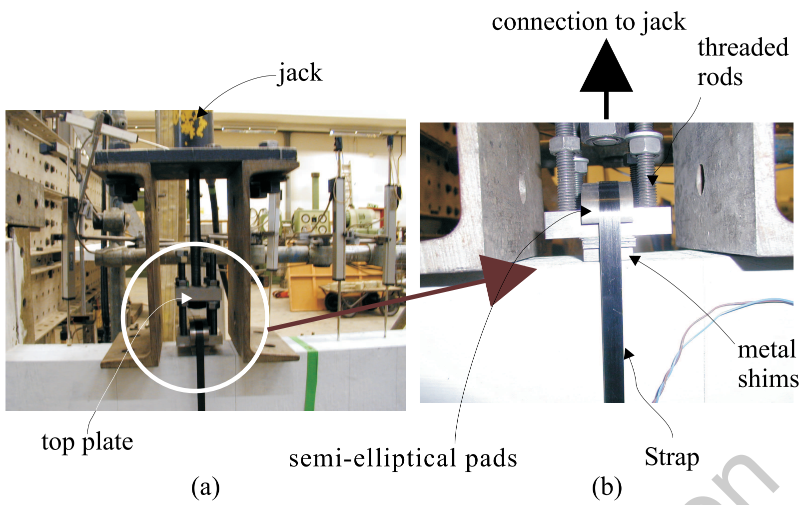


Figure 3: Prestressing arrangement for straps

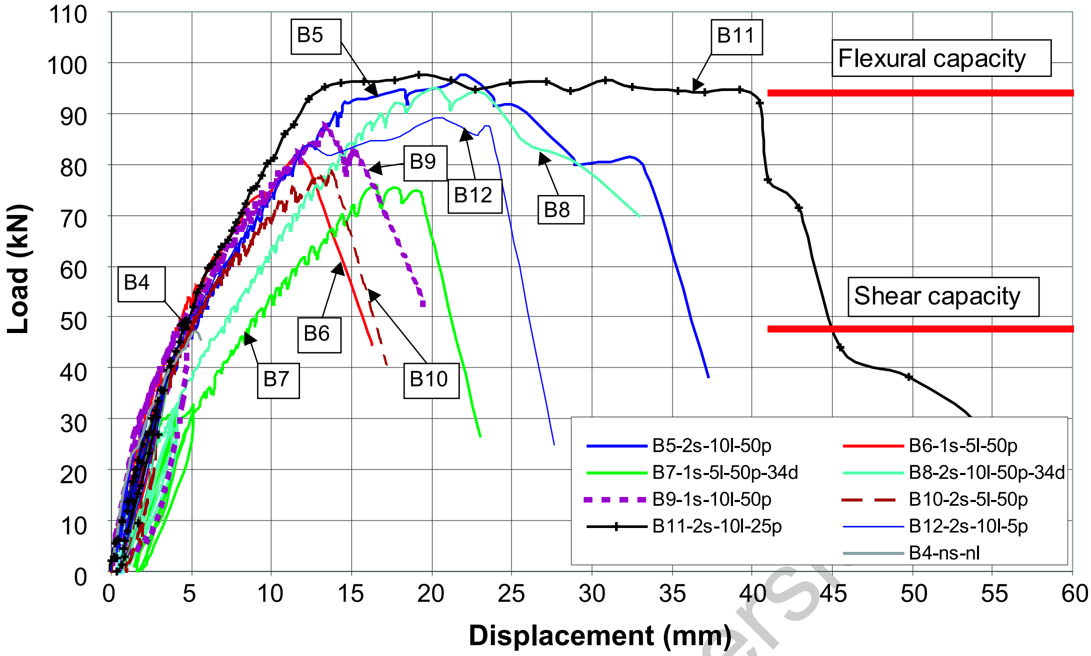


Figure 4: Load displacement curves

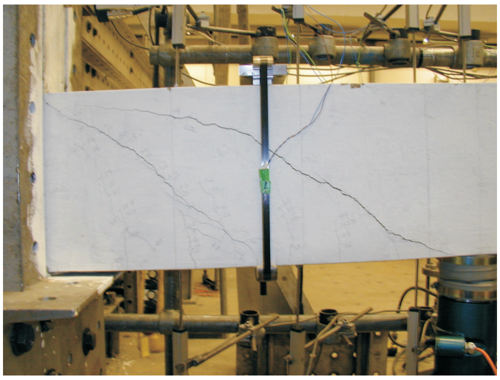


Figure 5: Beam 6 before strap rupture

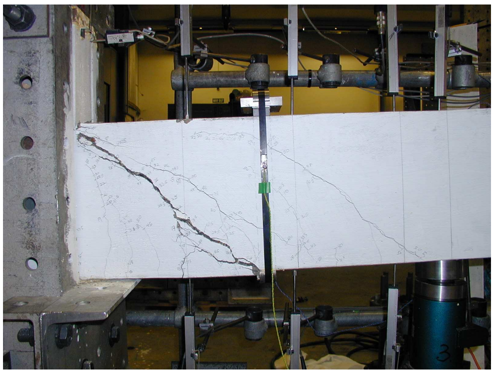


Figure 6: Beam 9 at failure

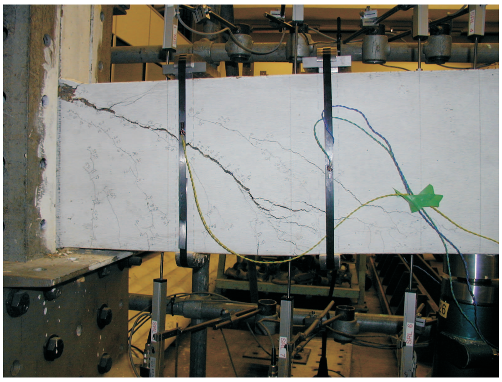
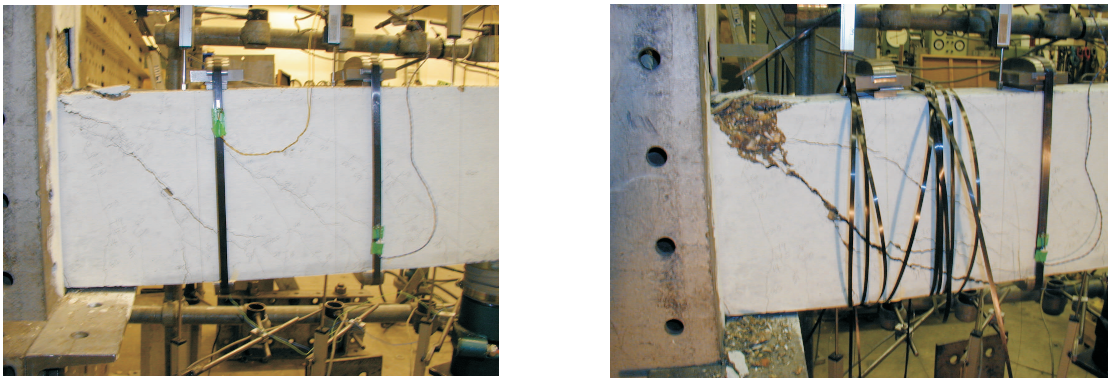


Figure 7: Beam 12 at peak load



(a) (b)

Figure 8: Beam 5 (a) at peak load and (b) after strap rupture

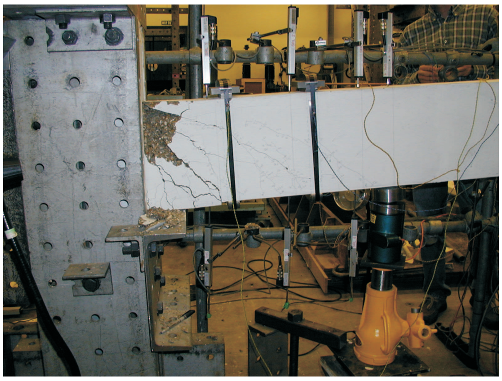


Figure 9: Beam 11 at failure

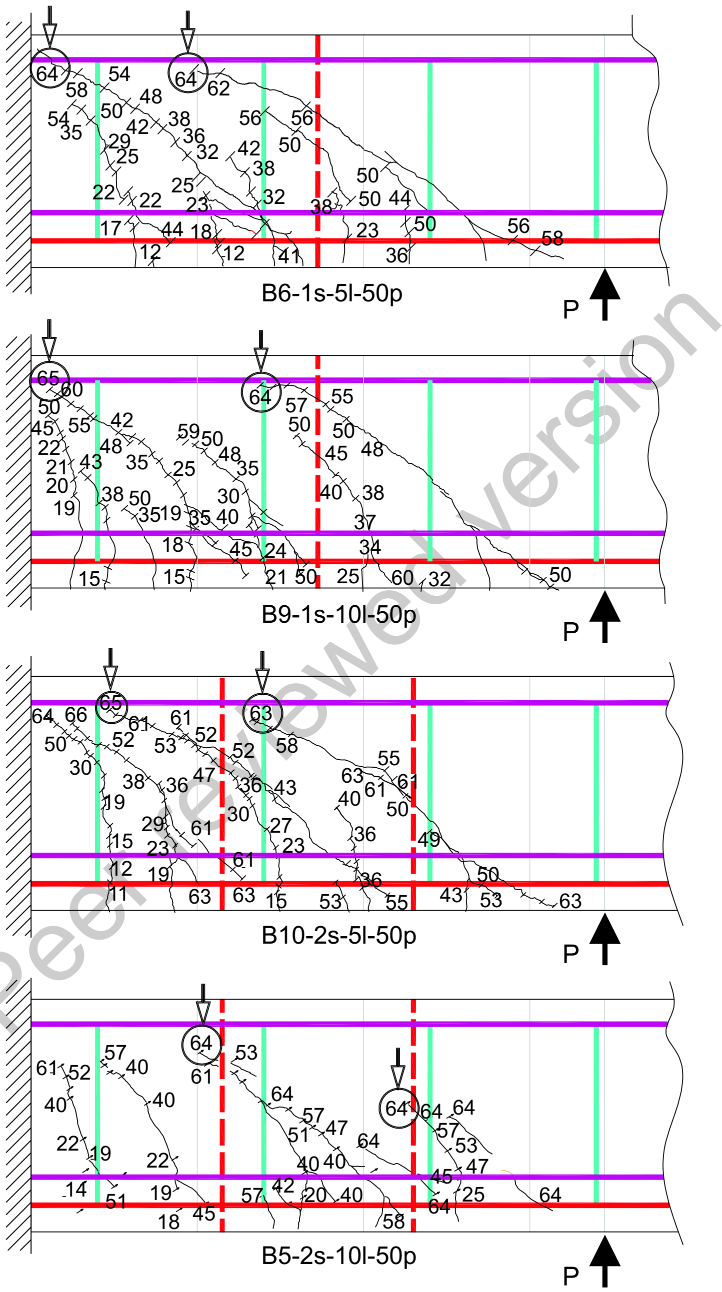


Figure 10: Beam 6, Beam 9, Beam 10 and Beam 5 crack patterns at 65 kN

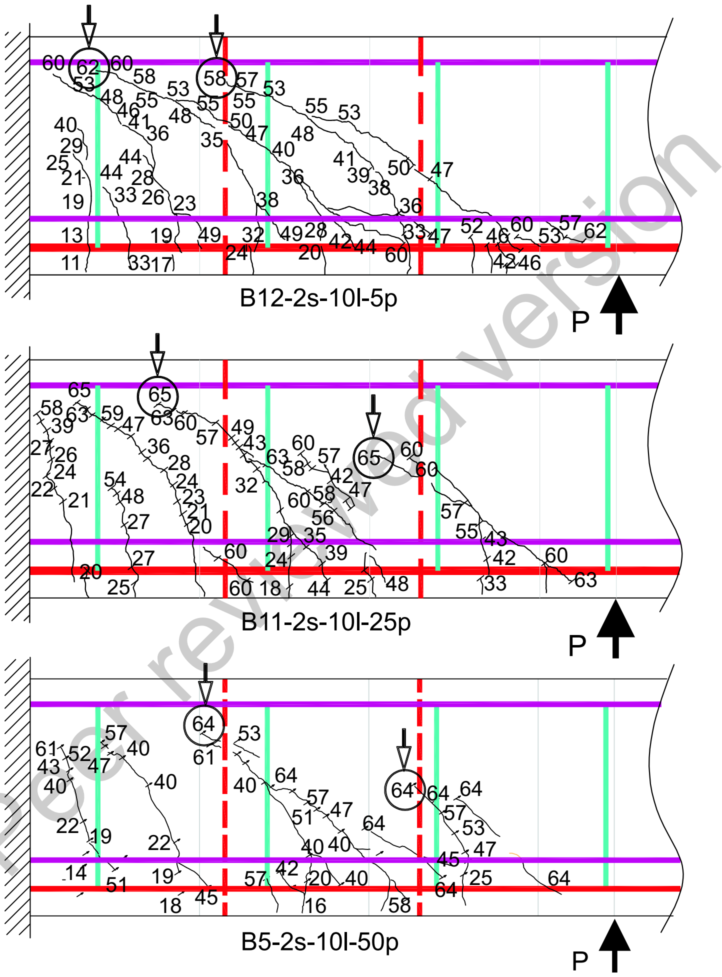


Figure 11: Comparison of crack patterns for beams with different initial prestress levels

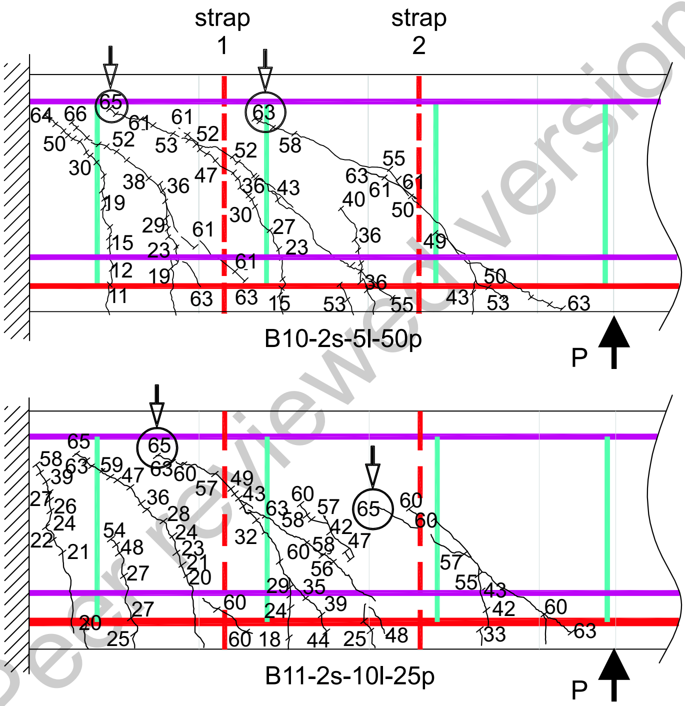


Figure 12: Comparison of beams with the same prestress force but different strap stiffness

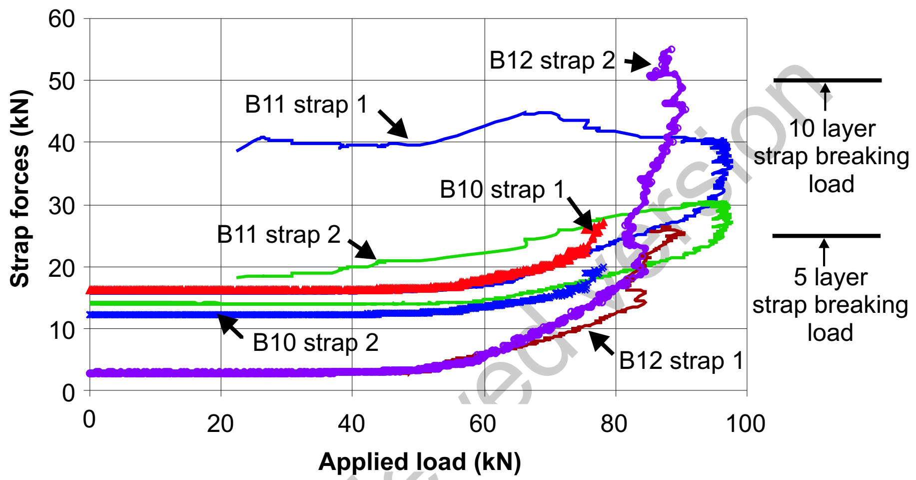


Figure 13: Force in straps - Beams 10, 11 and 12

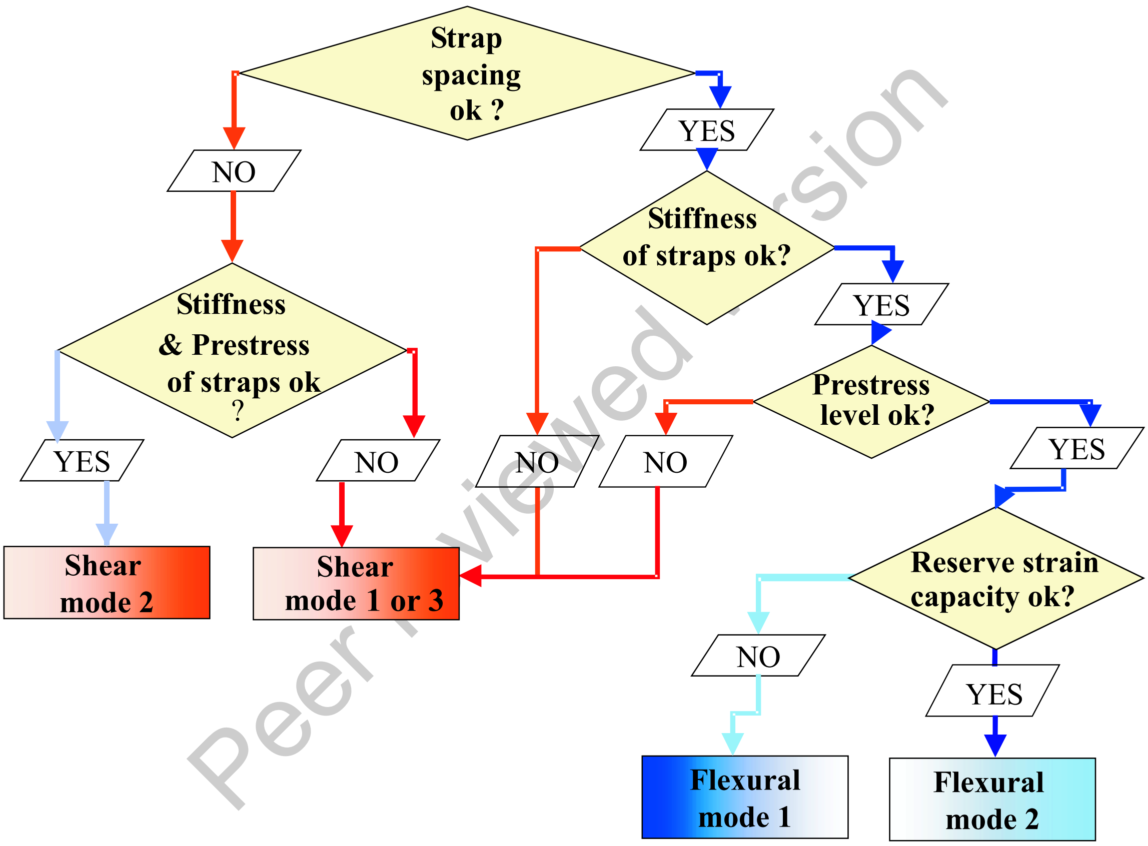


Figure 14: Overview of strengthening with straps